Surface Temperature Inversions and Risk of Off-Target Herbicide Damage in the Soybean- and Cotton-Growing Regions of the US

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Crop Management

Abstract

The approval of the dicamba-tolerant trait in soybean and cotton as well as new dicamba spray formulations to control weeds in cotton and soybean fields has resulted in broad usage of dicamba-based herbicides. As dicamba-based herbicide usage increased, reports of non-target crop damage dramatically increased. Temperature inversions have been implicated in this off-target damage. Short-term climatologies of surface inversions at six locations across the soybean- and cotton-growing regions of the US were developed for the period 15 May through 30 June between 2012 and 2017 using National Climate Reference Network measurements. Inversions occurred most nights, occasionally collapsing and then reforming in the same night. Inversions often formed before or around sunset as the surface temperature cooled more rapidly than the overlying air. Inversion development was similar for most of the soybean-growing region with the greatest change in temperature difference between the air and the ground occurring at sundown. Higher wind speeds corresponded to decreased inversion intensity and shortened the duration of the inversion. Differences in inversion conditions in 2017 versus those of 2013–2016 were not consistent; consequently, the increased occurrence of off-target damage by dicamba in 2017 cannot be explained by an increase in the number or intensity of inversions or differences in winds during inversions. The presence of inversions when they are not expected (before sunset, after sunrise and when winds exceed 3 mph) increases the risk of unexpected off-target crop damage. Since inversions are commonly a local phenomenon, predicting inversion occurrence requires understanding the conditions at specific locations.

T he approval of the dicamba (3,6-dichloro-2-methoxybenzoic acid) tolerant trait in soybean and cotton by the USDA in 2015 and the 2016 registration by the USEPA of new dicamba spray formulations approved for "over-the-top" use to control weeds in cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merr.] plants genetically engineered to resist dicamba has resulted in broad usage of the herbicide and tolerant-trait seeds. There have been significant off target movement concerns and non-target crop damage associated with dicamba. Dicamba has especially been implicated in extensive off-target crop damage in 2017 (Lipton, 2017).

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Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
1.609	mile, mi	kilometer, km (10^{-3} m)
5/9 (°F − 32)	Fahrenheit, °F	Celsius, °C
0.304	foot, ft	meter, m

Temperature inversions (air temperature increasing with height) have been implicated in this off-target damage (Cummins, 2018) due to the typically reduced herbicide mixing in the stable air of an inversion. This reduced mixing results in highly variable concentrations of the gases, vapors, or aerosol particles from point to point across the landscape (Mylne, 1992). The typical meandering plume drift of high concentrations of aerosols or vapors, when integrated over the duration of the inversion, could show any number of patterns as well as relatively consistent damage across entire fields (Mylne, 1992).

Temperature inversions over level ground typically are due to radiative cooling of the air near the ground or the advection of warm air over cooler ground (Oke, 1978; André and Mahrt, 1982). Advection-influenced radiative inversions will occur near water bodies and in valleys and swales of hilly terrain (Oke, 1978) as well as in regions with varying surface characteristics (Kaimal and Finnigan, 1994). Bodine et al. (2009) found that terrain elevation changes of as little as 20 ft could result in the establishment of inversion conditions.

Few climatological evaluations of temperature inversions have been made across the US. Hosler (1961) found inversion frequencies across the central US to range from 30 to 35% during the spring and summer (as percent of total hours). In contrast, Baynton et al. (1965) found spring and summer nocturnal inversions occurred about 90% of the time at a location near the Pacific Ocean. Neither of these studies addressed the occurrence of inversions at the ground surface. Studies of surface inversions have not been done due to lack of long-term measurements (National Research Council, 2009).

The occurrence and character of inversions at the ground were evaluated for seven continental United States Climate Reference Network (USCRN) locations between 15 May and 30 June over the years 2012–2017. The climate stations were grouped along a north–south axis across a 9° latitude range across the soybean cropping region (Sioux Falls, SD [43.7°N, 96.6°W, elevation 1574 ft]; Des Moines, IA [41.6°N, 93.3°W, elevation 921 ft]; Champaign, IL [40.1°N, 88.4°W, elevation 700 ft]; Salem, MO [37.6°N, 91.7°W, elevation 1198 ft]; and Holly Springs, MS [34.8°N, 89.4°W, elevation 484 ft]) and an east–west axis along a 17° longitude range across the cotton cropping region (Holly Springs, MS [34.8°N, 89.4°W, elevation 484 ft]; Muleshoe, TX [34.0°N, 102.8°W, elevation 3742 ft]). Holly Springs had measurements only for 2013 through 2017 while all other locations had measurements from the 2012 through 2017 period. All times are Central Daylight Savings time.

General Climate Conditions

A subset of the USCRN 5-min measurements were used in the analysis: mean air temperature (of three collocated sensors) at 5 ft, ground surface temperature, relative humidity and wetness, and wind speed at 5 ft (Diamond et al., 2013). Dew point temperatures were estimated based on hourly mean relative humidity and air temperature using an empirical formula of Lawrence (2005). It was assumed that the air temperature at the surface was identical to the surface temperature, and therefore the surface temperature could be used as a good proxy for air temperature at the surface. Dew deposition was assumed when the surface temperature was less than the dew point temperature. Given the relative humidity (RH) sensor error of ±5% near saturation (Diamond et al., 2013), relative humidity values above 94% (single-sided t test against a known 100% RH with a 95% confidence) were assumed to be indicative of fog. This is consistent with the 95% RH threshold used in the analysis Kim and Yum (2010).

Inversions were defined by a positive difference exceeding 1.2°F between the mean hourly air temperature at 5 ft and surface temperature (DT). This DT threshold was defined by the least significant difference in the measurements at a 95% confidence interval based on the USCRN triplicate measurement of air temperature (combined accuracy of 0.5°F) and the surface temperature measurement (accuracy of 0.9°F) (Diamond et al., 2013). The beginning and end of each inversion period was defined by the first and last sequential hour of an inversion. Inversions were described by mean wind speed, mean DT, and maximum difference in DT (DT_{max}) (van Hooijdonk et al., 2017).

Table 1. Daily meteorological conditions between 15 May and 30 June.

Location	Mean air temperature	Mean surface temperature	Mean wind speed
	°F		————mph————
Sioux Falls, SD	66.0	68.2	5.1
Des Moines, IA	68.5	69.3	5.4
Champaign, IL	70.0	70.0	5.4
Salem, MO	69.8	71.4	4.0
Holly Springs, MS	72.9	77.5	2.5
Muleshoe, TX	73.6	79.3	7.6

Table 2. Relationship of sunrise and sunset to ending and beginning of temperature inversions over the period of 15 May–30 June.

Location	Mean sunset (hh:mm)	Mean hour interval of inversion beginning	% of first inversions occurring before sunset	Mean sunrise (hh:mm)	Percent of last inversions occurring after sunrise
Sioux Falls, SD	21:03	19:00–19:59	96	05:50	4
Des Moines, IA	20:44	18:00–18:59	98	05:44	8
Champaign, IL	20:18	17:00–17:59	98	05:27	23
Salem, MO	20:24	18:00–18:59	98	05:47	4
Holly Springs, MS	20:08	19:00–19:59	76	05:47	1
Muleshoe, TX	20:59	19:00–19:59	94	06:42	17

Over the period 2012 through 2017, the mean air temperature across the north–south soybean-growing locations (Sioux Falls, Des Moines, Champaign, and Holly Springs) ranged from 66.0 to 72.9°F with a trend of cooler air and surface temperatures with increasing latitude (Table 1). Across the east–west cotton-growing transect locations (Holly Springs and Muleshoe), the mean air temperature ranged from 72.9 to 73.6°F (Table 1). The climatological mean wind speed ranged widely across all locations: lowest at Holly Springs and highest at the high plains location of Muleshoe.

Inversion Development

Temperature inversions typically occurred between 5 pm and 6 am (Table 2). The mean onset of the initial late-afternoon inversion was at least an hour before sunset (Table 2). Inversions at all locations began before sunset (94 to 98%), except at Holly Springs where only 76% of inversions began before sunset (Table 2), consistent with the findings of Molga (1962) and Geiger (1965). The frequency of sustained inversions (>3-h duration) varied greatly over the 2012–2017 period (Table 3). On many days, an inversion would develop, break down, and then re-develop, resulting in more inversions than the number of days in the period (47 days).

On average, across the entire period of record, inversions were most common at Champaign and Salem and least common at Holly Springs (Table 3).

Inversions generally formed under lower wind speeds and surface temperatures than when inversions did not form (Table 4). The DT_{max} typically occurred a few hours (around 8 pm) after the inversions started forming at Sioux Falls, Des Moines, Champaign, and Salem (Fig. 1A). Temperature inversions did not typically intensify after 11 pm. The last hour with an inversion in the morning typically occurred before sunrise (Table 2). Less than 5% of inversions ended after sunrise, except at Des Moines, Champaign, and Muleshoe (Table 2).

Inversions occurring before 6 pm were typically associated with relatively high wind speeds consistent with advection contributing to the inversion (Fig. 1B). Inversions during the hours after 6 pm typically had wind speeds less than 4 mph (Fig. 1B). While winds also dropped by 7 pm at Muleshoe (TX), the mean speed did not drop below 3 mph (Fig. 1B). The wind speeds during inversions at Muleshoe over the 7 to 10 pm interval are similar

to the mean wind speed for all hours (Table 1). The winds did not differ greatly when inversions were present over the 7 to 10 pm interval at both Holly Springs and Muleshoe (Table 4).

As previously discussed, inversions typically formed as the surface temperature decreased more rapidly than the air temperature. Under inversion conditions, the surface temperature was frequently lower than the dew point temperature of the air, resulting in dew on the surface. Along the soybean region transect, the frequency of dew increased from north to south, starting at roughly 50% of the inversion hours at Sioux Falls and ending at roughly 80% of the inversion hours in Holly Springs (Table 4). Along the cotton region transect, the frequency of dew during inversions decreased east to west with roughly 80 to 90% of the inversion hours having dew east of the Mississippi River and only 21% in Muleshoe (Table 4).

The presence of dew on the surface does not assure the formation of fog in the air over the surface since the air temperature near the surface is higher than the surface temperature. The frequency of fog formation at 5 ft above the surface under inversion conditions was lower during inversions than non-inversions (Table 4). This might be expected, since: (1) under inversion conditions, the increasing air temperature with height would be expected to limit the depth of any fog present at the surface; and (2) under non-inversion conditions, the air temperature decreases with height and the potential for fog at the surface to be relatively thick increases.

Were Conditions during 2017 Different?

Differences between the prevalence and characteristics of surface inversions over the 2012 (or 2013) through

Table 3. Sustained inversion events between 15 May and 30 June.

Location	No. inversions greater than 3h/yr[†]					Mean 2012–2016	2017
	2012	2013	2014	2015	2016		
Sioux Falls, SD	44	47	53	47	55	49	54
Des Moines, IA	2	29	39	32	29	26	38
Champaign, IL	58	60	60	43	57	56	47
Salem, MO	57	57	52	49	58	55	53
Holly Springs, MS	–	31	13	26	42	28	50
Muleshoe, TX	62	56	53	25	45	48	39

† More than one inversion per day possible.

Table 4. Mean characteristics of conditions between 7 and 10 pm.

Location	Surface temp. (°F) No inversion	Surface temp. (°F) Inversion	Air temp. (°F) No inversion	Air temp. (°F) Inversion	Wind speed (mph) No inversion	Wind speed (mph) Inversion	Dew frequency (%) No inversion	Dew frequency (%) Inversion	Fog frequency at 5 ft (%) No inversion	Fog frequency at 5 ft (%) Inversion
	————————°F————————				———mph———		———————————%———————————			
Sioux Falls, SD	62.4	62.8	63.0	68.0	5.1	3.1	4	47	9	0
Des Moines, IA	66.9	63.3	67.5	68.7	4.9	3.4	9	66	12	1
Champaign, IL	65.1	63.9	66.4	69.1	4.9	3.4	9	57	5	1
Salem, MO	63.0	64.2	64.0	69.3	3.1	2.7	12	77	13	10
Holly Springs, MS	69.6	68.2	70.0	71.6	1.3	1.1	9	81	2	2
Muleshoe, TX	72.9	72.5	72.5	77.4	7.1	7.2	1	21	2	0

2016 period were compared with those in 2017 to evaluate whether the inversion conditions were substantially different in 2017 and help explain the large number of off-target damage complaints in 2017. The number of inversions in 2017 was not significantly greater than the prior 5 years across all locations. While the number of sustained inversions were greater in 2017 than the mean of the prior 5 years at three of the seven locations (Des Moines and Holly Springs) (Table 3), the differences were not significantly different (Student's t test, $P = 0.1$). Afternoon inversions began 1 h earlier for Holly Springs and Salem in 2017 than 2012–2016.

The differential cooling of the ground and the air over the ground generally started at lower temperatures in 2017 than the prior 5 years. In general, air and surface temperatures were cooler between 6 and 9 pm in 2017 than the prior 5 years (except for Champaign and Muleshoe; Table 5). The mean intensity of inversions (DT) over the 6 to 9 pm window of time when inversions typically form was greater in 2017 at Sioux Falls, Des Moines, and Holly Springs but less at Champaign, Salem, and Muleshoe (Table 5). The changes in intensity of inversion did not correspond with changes in the mean wind speed: Mean wind speed was greater at Des Moines and Champaign, but the same or less for all other locations (Table 5). Higher wind speeds at Des Moines and Champaign did correspond with fewer inversions in 2017 than the prior 5 years (Table 3).
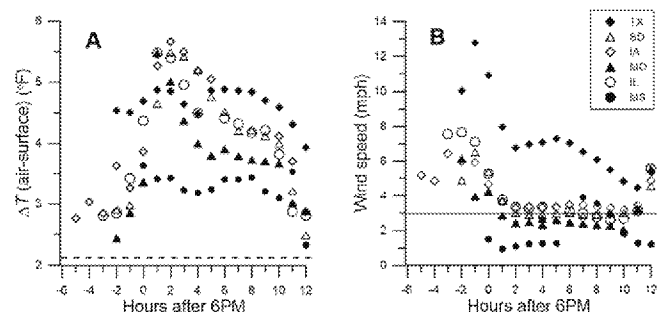

Fig. 1. Mean difference in air and surface temperatures and wind speeds during inversions. Mean hourly air temperature – surface temperature (Panel A) and wind speeds (Panel B) during inversions at all locations. The dashed line in Panel B indicates the inversion detection threshold. The solid horizontal line in Panel B indicates the 3 mph threshold wind speed indicated in dicamba herbicide labels.

Implications

The application labels of 2018 dicamba-based herbicide (e.g., Anonymous 2018a, 2018b) indicate, "Do not apply this product between sunset and sunrise... Temperature inversions can begin to form as the sun sets...." Based on this analysis of the conditions between 15 May and 30 June, surface inversions at all locations often began at least 1 h before sundown (Table 2). The likelihood of an inversion in the hour before sunset was approximately 50% at Des Moines, Champaign, Salem, and Muleshoe but less than 30% at Sioux Falls and Holly Springs. Thus, at most locations evaluated, there was at least 1 h in which an inversion was likely to form and still be within the label application guidelines.

Dicamba product labels indicate that surface inversions will dissipate at sunrise (Anonymous 2018a, 2018b). This statement was generally supported by the low fraction of inversions ending after sunrise (Table 2). However, the relatively high fraction of inversions not ending at sunrise at Champaign and Muleshoe suggests that the general assumption of no inversions after sunrise induces risk for some locations.

Dicamba product labels also indicate that fog is a good indicator of the presence of inversions (Anonymous 2018a, 2018b). Although this study could not evaluate the likelihood of occurrence of fog lower than 5 ft high, fog at 5 ft was more likely to occur when there was no inversion than when there was an inversion. Holly Springs was the only location where fog occurred as frequently during inversions as not.

Table 5. Change in mean conditions between 6 and 9 pm in 2017 relative to 2012–2016.

Location	Change: 2017–(2012–2016) Air temp.	Change: 2017–(2012–2016) Surface temp.	Change: 2017–(2012–2016) DT†	Change: 2017–(2012–2016) Wind speed
	————————°F————————			mph
Sioux Falls, SD	–1.4	–3.1	1.6	0.0
Des Moines, IA	0.0	–2.0	2.0	0.4
Champaign, IL	0.7	2.2	–1.4	1.1
Salem, MO	–1.4	–0.9	–0.5	–0.2
Holly Springs, MS	–0.9	–2.9	2.2	–0.2
Muleshoe, TX	0.4	1.8	–1.4	–0.7

† DT, mean hourly air temperature- surface temperature.

Dicamba labels indicate that surface inversions occur when winds are less than 3 mph (Anonymous 2018a, 2018b); the mean wind speed during most inversions (Table 4) was greater than the 3 mph. Consequently, the assumption that temperature inversions occur when the winds are less than 3 mph is incorrect. Since inversions indicate poor mixing of the surface air, the presence of inversions when they are not expected (before sunset and under winds greater than 3 mph) increased the risk of unexpected off-target crop damage.

Differences in inversion conditions in 2017 versus those of 2013–2016 were not consistent across the soybean- or cotton-growing regions. Consequently, the increased occurrence of off-target damage by dicamba in 2017 cannot be clearly explained by an increase in the number of inversions, the intensity of inversions, or the winds during inversions.

Surface temperature inversions described here represent conditions over open, flat grass surfaces. The presence of trees, terrain elevation variations, and variable ground surface conditions associated with cropped land will result in differing inversions conditions.

Acknowledgments

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